

Article

Copper–Ammonia–Thiosulfate Leaching of High-Sulfide Concentrates: Process Optimization and Additive Effects on Gold Extraction

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Abstract: This research focuses on finding an environmentally friendly method for extracting gold from a sulfide flotation concentrate. In this study, an ammonia–copper–thiosulfate leaching system was utilized for the extraction of gold. The flotation concentrate sample contains about 190 ppm of gold, 160 ppm of silver, and 6.89% of copper. To achieve an optimized gold extraction, various parameters, such as thiosulfate, ammonia and copper concentrations, pulp density, pH, stirring rate, temperature, and time, were investigated. About 87% of gold was leached under the following conditions: 0.5 M $S_2O_3^{2-}$, 1.0 M NH_3 , 0.1 M Cu^{2+} , a stirring rate of 350 rpm, a pH of 12, a pulp density of 10% solids, a temperature of 25 °C, and a leaching time of 2 h. Additionally, to improve the economic effectiveness of the leaching system, thiosulfate consumption was investigated by utilizing different additives, such as diethylenetriamine (DETA), glycerol, and ammonium dihydrogen phosphate (ADP). The results showed that with the use of ADP, gold extraction increased from 87% to 91% while reducing copper dissolution. Additionally, the thiosulfate consumption also decreased from 0.37 M to 0.3 M. The inclusion of ADP was particularly effective, enhancing gold extraction efficiency and reducing reagent consumption, thereby making the process more sustainable. Considering the high economic value of gold, the optimization of recovery efficiency is prioritized over reagent costs in this study. Overall, this study indicates that the optimized ammonia–copper–thiosulfate leaching system with ADP additive is a promising environmentally friendly method for the extraction of gold.

Keywords: gold leaching; ammonia–copper–thiosulfate; sulfide concentrate; additives; consumption



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1. Introduction

July 2023 marked the hottest month on record, signaling that an “era of boiling has arrived”, as reported by UN News. One important concern is the increasing level of greenhouse gases resulting from industrial activities [1] leading to climate change. This situation initiated global efforts to achieve a Carbon Neutral Society, in which the mitigation of climate change is maintained [2].

The role of renewable energy has attracted increased attention because it reduces the usage of fossil fuels and the release of greenhouse gases. However, the production of renewable energy technologies, such as solar panels, wind turbines, and fuel cells, requires critical metals. Along with the critical metals, gold (Au), silver (Ag), and copper (Cu) play an important role in green energy technologies [3–5]. Gold is used in various green energy technologies, such as electro-vehicle power generators, wind turbine generators, and solar photovoltaic cells. For this reason, it is crucial to find sustainable methods for extracting gold that minimize environmental impact.

In gold hydrometallurgy, cyanide technology has long been utilized for gold extraction due to its efficiency; however, many ores exhibit refractoriness to the conventional cyanidation process due to the presence of substances like carbon, sulfides, and tellurium, which complicates gold recovery [6]. Additionally, the environmental impact of cyanide has raised significant concerns [7,8]. The release of toxic cyanide compounds into the environment poses serious risks to the ecosystem and human health. In response to these concerns, researchers have been exploring alternative methods, such as thiosulfate leaching, specifically for its advantages like non-toxicity and a faster leaching rate. Arslan and Sayiner (2008) highlighted the potential of ammoniacal thiosulfate solutions for leaching gold and silver, noting high recovery rates under optimized conditions, thus supporting thiosulfate as a viable and less harmful alternative [9]. Additionally, alternatives such as iodine–iodide and thiourea leaching have also been studied [10,11], each presenting unique benefits over traditional cyanide. This research aims to contribute to the development of non-cyanide gold extraction systems, thereby promoting safer and more sustainable mining practices. Significantly, this study is the first to investigate the use of glycerol and ammonium dihydrogen phosphate (ADP) as additives in the thiosulfate leaching system, aiming to enhance both the efficiency and sustainability of gold extraction. For example, Mohammadi et al. (2017) investigated the leaching of gold from refractory oxide gold ores, and the results showed that 55% of Au was extracted by utilizing 0.1 M $\text{Na}_2\text{S}_2\text{O}_3$, 0.0125 M CuSO_4 , and a 3 M ammonium concentration for 16 h [12]. Moreover, Jeon reported that more than 99% of Au was successfully leached using 1 M $\text{Na}_2\text{S}_2\text{O}_3$, 10 mM CuSO_4 , and a 1 M ammonium concentration, with a treatment duration of 24 h in the presence of oxygen [13].

However, thiosulfate leaching also presents several limitations, including high reagent consumption due to decomposition, especially in complex mineralogical ores [14–16]. Xu et al. mentioned that the decomposition of thiosulfate in leaching processes presents significant drawbacks, including increased reagent consumption, higher operational costs, complex process control, interference with gold recovery, and environmental challenges [17]. These challenges render thiosulfate leaching impractical for use in real-world hydrometallurgical plants. Consequently, extensive research has been conducted to identify optimal conditions to mitigate these issues.

To overcome the challenges associated with thiosulfate leaching, various additives have been investigated to enhance gold recovery and reduce reagent consumption. Chelating agents, such as ethylenediaminetetraacetic acid (EDTA) and diethylenetriamine (DETA), have been shown to stabilize copper (II) ions, thereby preventing their precipitation and maintaining an optimal catalytic effect on gold oxidation. Similarly, glycine, an amino acid, acts as a stabilizer in alkaline thiosulfate solutions, forming stable metal complexes that promote gold dissolution. Glycerol, a trihydroxy alcohol, has demonstrated the ability to reduce the rate of thiosulfate decomposition, thus improving overall leaching efficiency. Ammonium dihydrogen phosphate (ADP) is another promising additive, as it contributes to pH stabilization while simultaneously reducing excessive copper dissolution, which is known to interfere with selective gold recovery. The use of these additives offers potential

advantages in minimizing thiosulfate losses while ensuring an effective and environmentally friendly gold extraction process. This study systematically investigates these additives to identify the most suitable conditions for optimizing the thiosulfate leaching of gold in high-sulfide-containing flotation concentrates.

Although other additives, such as citrate and hexametaphosphate, have also shown promise [18,19], ADP and glycerol were prioritized in this study due to their unique dual-function properties. For example, citrate forms stable complexes with copper and is effective at high temperatures. However, it can lower redox potential and requires careful control of reagent concentrations. Hexametaphosphate enhances thiosulfate stability and gold extraction but shows reduced efficiency beyond optimal dosages and has a limited pH stabilization effect. In contrast, glycerol not only suppresses thiosulfate decomposition but also stabilizes the leaching environment, while ADP provides both pH control and reduced copper dissolution, which are critical for high-sulfide flotation concentrates. These synergistic effects make ADP and glycerol more suitable for practical and scalable applications in complex ore systems.

However, the implementation of ammoniacal thiosulfate leaching presents several technological challenges that must be addressed to ensure its practical application. One major challenge is the rapid decomposition of thiosulfate, which leads to excessive reagent consumption and increases operational costs. The formation of unwanted by-products, such as tetrathionates and polythionates, further complicates process control and may interfere with gold recovery. Additionally, the selective dissolution of gold in the presence of copper and silver remains difficult, as high concentrations of copper ions can promote undesirable side reactions that hinder the efficiency of gold extraction. Ensuring pH stability and redox potential control is another crucial factor, as variations in these parameters significantly influence reagent stability and gold dissolution kinetics. Given these challenges, this study explores the use of stabilizing additives to improve the efficiency and selectivity of the leaching process, ultimately aiming to develop a more economically and environmentally viable alternative to cyanide leaching.

Moreover, the findings from this study may suggest practical applications for the ammonia–copper–thiosulfate leaching system in the extraction of gold from high-sulfide-containing flotation concentrates, emphasizing the potential for optimized operational conditions that enhance both the environmental sustainability and economic viability of mining operations.

2. Materials and Methods

2.1. Materials

A flotation concentrate was used in this study. This gold flotation concentrate sample is processed under specific flotation conditions. The chemical composition of the flotation concentrate was analyzed using X-ray fluorescence (XRF, ZSX Primus II, Rigaku Corporation, Tokyo, Japan). To determine the gold and silver content, the sample was dissolved in aqua regia and nitric acid, respectively, then filtered and analyzed using Microwave Plasma Atomic Emission Spectroscopy (MP-AES, Agilent 4210, Agilent Technologies, Santa Clara, CA, USA). The obtained results are presented in Table 1.

Table 1. Chemical composition of the flotation concentrate sample.

Element	O	Si	Fe	S	Cu	Al	C	Zn	Pb	Ag	Au
Contents (wt.%)	36.17	18.73	11.30	11.06	6.89	6.55	4.08	0.98	0.29	160 ¹	190 ¹

¹ Au and Ag are presented in ppm due to their trace concentrations.

The particle size distribution of the flotation concentrate sample was characterized using a particle size analyzer (Microtrac, MT3300EXII, Nikkiso Group, Osaka, Japan) (Figure 1). The particle size analysis showed that the D50 of the sample was 40 μm . The main components in the sample were identified using an X-ray diffractometer (XRD, RINT-2200/PC, Rigaku, Tokyo, Japan) and included quartz (SiO_2) (55%), magnetite (Fe_3O_4) (2.9%), pyrite (FeS_2) (25%), chalcopyrite (CuFeS_2) (6%), alunite [$\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$] (1.4%), and chalcocite (Cu_2S) (1.8%), as shown in Figure 2.

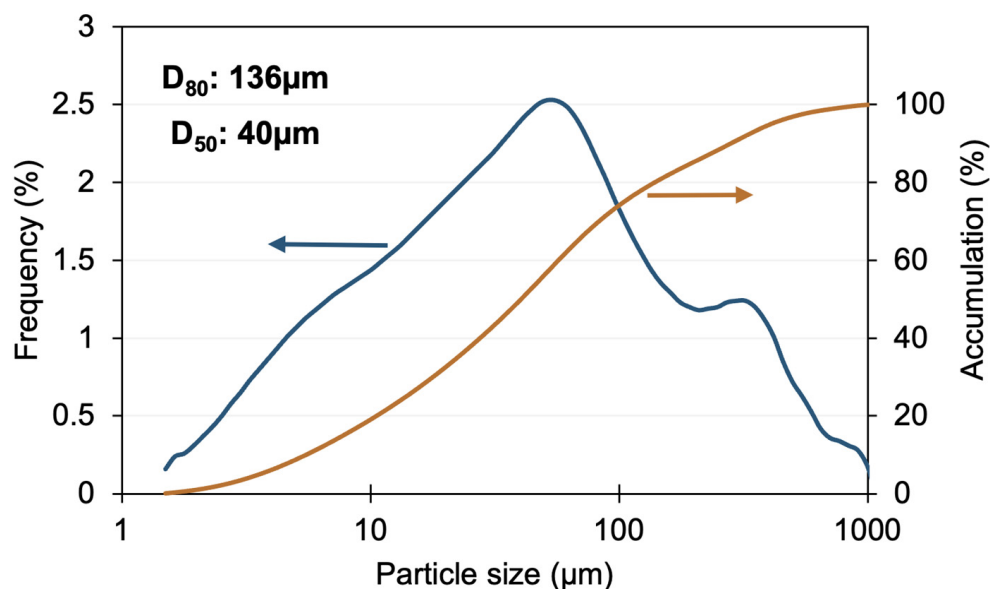


Figure 1. Particle size distribution of flotation concentrate.

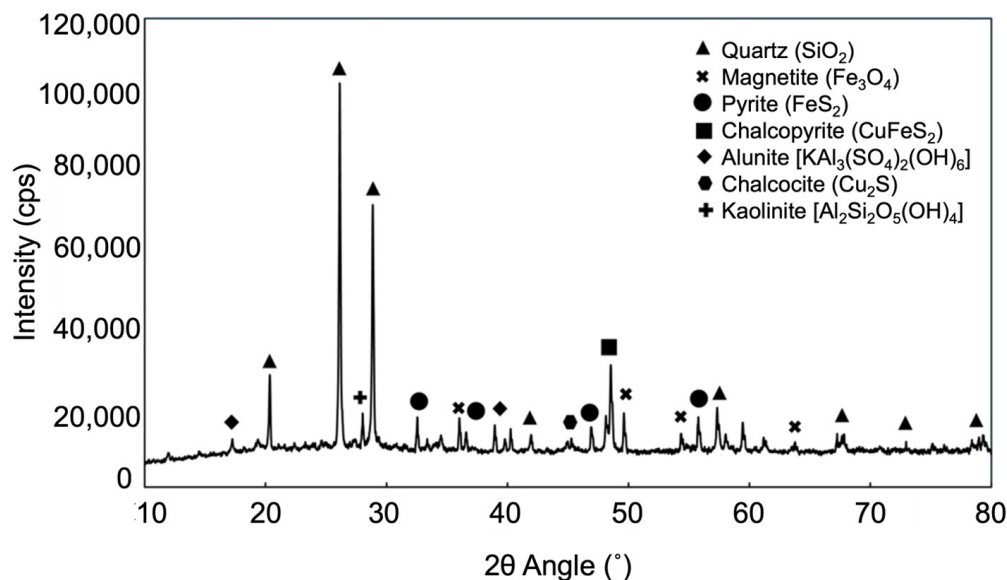


Figure 2. X-ray diffraction pattern of flotation concentrate.

The SEM analysis confirms the presence of gangue minerals, such as quartz, and ore minerals, such as galena, pyrite, and calaverite, which are illustrated in Figure 3 as the primary gold-bearing minerals.

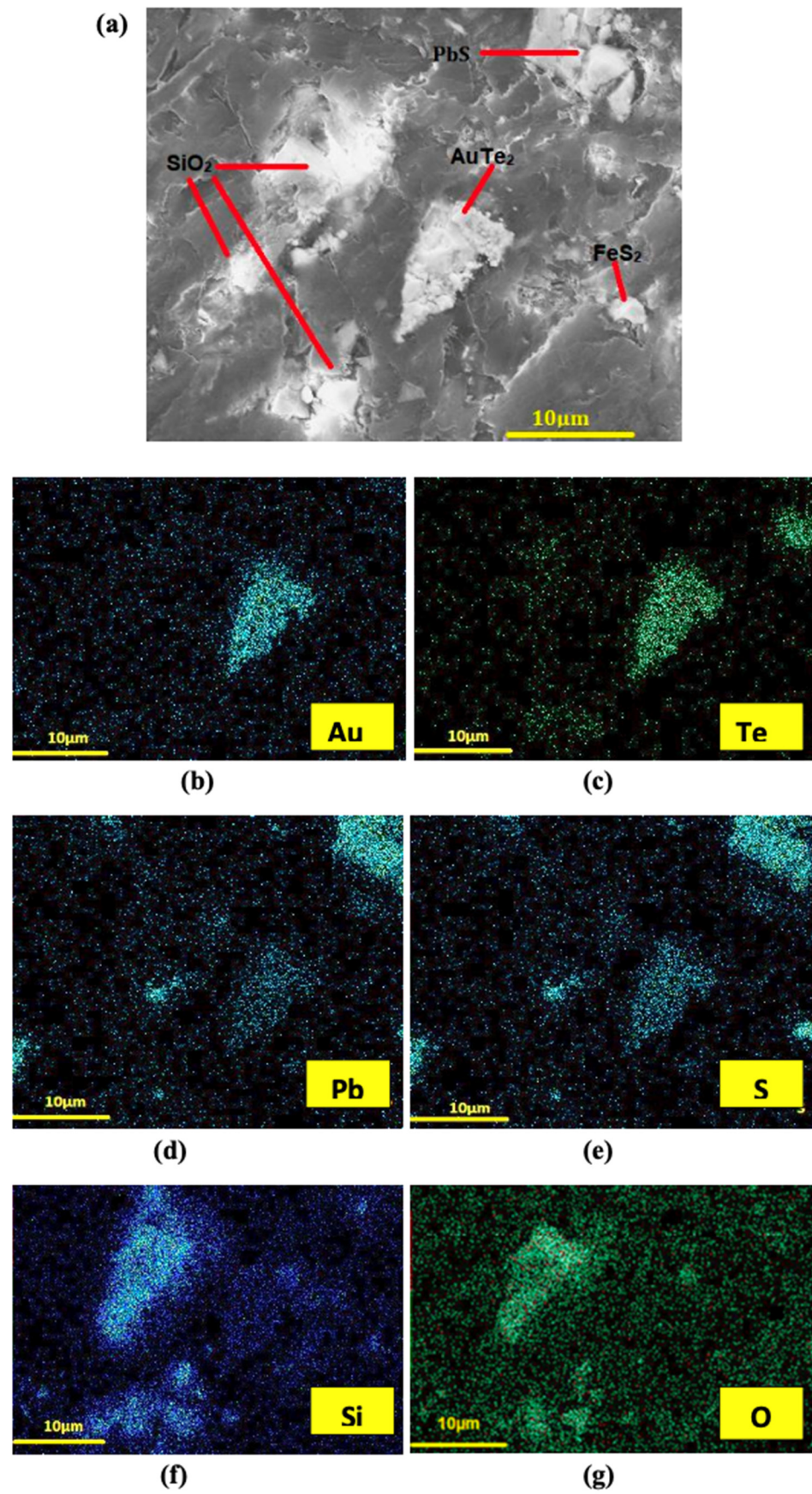


Figure 3. (a) SEM image and (b–g) element mapping of the flotation concentrate.

2.2. Leaching Experiments

Batch leaching experiments were conducted to investigate the effects of leaching time (1–12 h), pulp density (10–50%), pH (9.5–12), temperature (25–60 °C), agitation speed (350–650 rpm), CuSO₄ concentration (0.01–0.3 M), Na₂S₂O₃ concentration (0.05–2 M), and total ammonia concentration (0.1–3 M) on the extractions of gold, silver, and copper from the concentrate sample. To ensure the reproducibility of the gold extraction results, all experiments targeting Au were conducted in triplicate, and the average values with standard deviations were reported.

The major leaching reagents were copper (II), ammonia (NH₃), and thiosulfate (S₂O₃^{2−}) in the forms of sodium thiosulfate (Na₂S₂O₃), copper sulfate pentahydrate (CuSO₄·5H₂O), and ammonia (NH₃), respectively. All leaching tests were carried out by mixing a known number of samples with 40 mL of ammonium–thiosulfate solutions in a 50 mL Erlenmeyer flask. The slurry pH and ORP were measured using a pH meter (TOKO-TPX-999i, Toko Kagaku Kenkyusho, Yamato-shi, Japan). Filtration of the leach slurry was performed using a vacuum filter, and residues were dried at 80 °C in an electric drying oven (ADVANTEC-DRD420DA, Tokyo, Japan) for 24 h.

The leach filtrate was diluted when necessary and analyzed for Au, Ag, and Cu using MP-AES, while the residues were further studied using XRF, XRD, and SEM.

Triplicate leaching and analytical tests were applied only for Au extraction to quantify reproducibility.

Subsequently, the effects of the additives were investigated to determine each additive's potential for reducing thiosulfate consumption without hindering the leaching of Au and Ag and, possibly, for increasing the extraction of Au and Ag.

The five (5) additives investigated included glycerol (C₃H₈O₃), EDTA (C₁₀H₁₆N₂O₈), glycine (C₂H₅NO₂), ammonium dihydrogen phosphate (NH₄H₂PO₄), and DETA (C₄H₁₃N₃) (Wako Pure Chemical Industries, Ltd., Osaka, Japan). In separate flasks, a 0.1 M concentration of each reagent was added and leached under optimized conditions. The selection of a 0.1 M additive concentration was based on preliminary tests and stoichiometric considerations, ensuring an effective molar ratio to Cu²⁺ ions to provide a sufficient complexing or stabilizing effect within the leaching process.

The remaining slurry was filtered to collect the filtrate for MP-AES analysis, while the leach residue was dried and analyzed using XRF and MP-AES.

3. Results and Discussion

3.1. Leaching of Gold from Flotation Concentrate

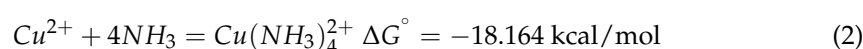
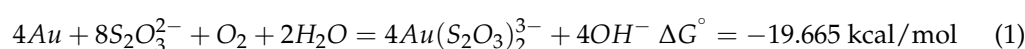
The thiosulfate-only leaching of gold under alkaline or neutral conditions is a very slow process in the presence of oxygen (1). Moreover, studies have demonstrated that in the absence of copper–ammonia, thiosulfate decomposes on the surface of gold, forming a sulfur coating that leads to gold passivation [15,17,20–23]. The effective method for gold dissolution involves the combination of thiosulfate and Cu²⁺ ions as an oxidant, with ammonia serving as a stabilizer [24,25].

Previous studies on ammonia–copper–thiosulfate leaching have demonstrated varying levels of gold recovery depending on the ore type and leaching conditions. For instance, Jeon et al. (2020) [13] reported a gold extraction efficiency of over 99% from printed circuit boards using 1 M Na₂S₂O₃, 10 mM CuSO₄, and 1 M ammonium for 24 h under oxygen presence conditions, while Yener Yazıcı et al. (2011) [26] achieved ~62% gold extraction from a copper-rich gold ore using 0.5 M S₂O₃^{2−}, 25 mM Cu²⁺, and 0.5 mM NH₃ under similar leaching conditions. In contrast, this study achieved 87% gold extraction under optimized conditions of 0.5 M thiosulfate, 1.0 M ammonia, and 0.1 M Cu²⁺ at pH 12, with a leaching duration of 2 h. The significant improvement in gold recovery observed in this

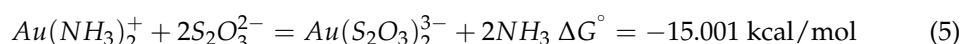
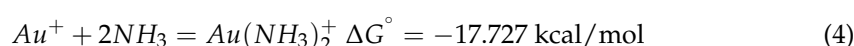
study, compared to the results of Yener Yazıcı et al. (2011) [26], can be attributed to the optimized pH conditions and controlled reagent concentrations, which minimized thiosulfate decomposition. Importantly, our results align with the findings of Oraby et al., 2014, who demonstrated that silver content significantly enhances gold dissolution in thiosulfate solutions, with dissolution rates for gold increasing in the presence of higher silver contents [27]. However, the slightly lower recovery compared to Jeon et al. (2020) [13] suggests that electronic waste materials may have different leaching efficiencies due to the absence of certain sulfide minerals that contribute to reagent consumption in natural ores.

The comparisons highlight that while thiosulfate leaching provides a viable alternative to cyanide-based extraction, the efficiency of the system is highly dependent on process optimization. The integration of various additives in this study additionally reduces reagent consumption, making the process both environmentally and economically sustainable.

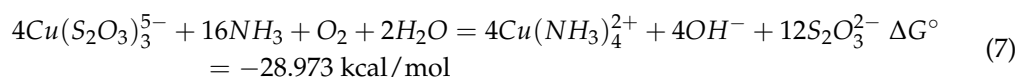
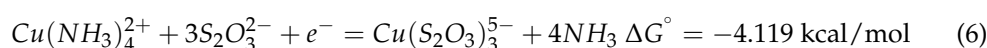
Initially, the cupric tetraammonia complex is formed during the preparation of the lixiviant (2), followed by continuous electrochemical reactions, as shown in Equations (3)–(7).



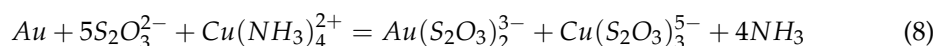
Anode reactions:



Cathode reactions:



At the anode, gold is oxidized to form Au^+ ions. These ions then react with ammonia to form a gold–ammonia complex, $Au(NH_3)_2^+$, which subsequently reacts with thiosulfate to produce a stable gold–thiosulfate complex, $Au(S_2O_3)_2^{3-}$, while releasing ammonia back into solution. At the cathode, the cupric ammonia complex, $Cu(NH_3)_4^{2+}$, reacts with thiosulfate and gains an electron to form a copper–thiosulfate complex, $Cu(S_2O_3)_3^{5-}$, while releasing ammonia. The copper–thiosulfate complex is then regenerated into the cupric ammonia complex in the presence of oxygen, water, and ammonia, producing hydroxide ions and additional thiosulfate. The overall dissolution reaction for gold in copper–ammonia–thiosulfate solutions can be expressed as reaction (8) as follows:



To increase gold extraction, optimal operating conditions for leach control variables, such as temperature, pH, pulp density, stirring rate, and time, were individually tested. Since too much or too little of each reagent can either hinder or enhance the gold leaching process, it was therefore paramount to experimentally determine the optimum dosage for each reagent.

3.1.1. Effect of Thiosulfate on Metal Extraction

The effect of thiosulfate on leaching is shown in Figure 4a. Leaching experiments were conducted within a concentration range of 0.05 M to 2 M while maintaining the following constant parameters: 0.1 M Cu^{2+} , 0.05 M NH_3 , a stirring rate of 400 rpm, a pulp density of 20%, a leaching time of 1 h, a temperature of 25 °C, and a pH of 10. The efficiency of leaching for all target metals was below one-fifth. Gold and silver extraction increased with an increase in the thiosulfate concentration of 0.5 M, then decreased with a subsequent increase in the thiosulfate concentration. Conversely, the leaching of copper exhibited a slight increase with the rising thiosulfate concentration, stabilizing at less than 10% at a thiosulfate concentration of 2 M. At a concentration higher than 0.5 M, Au and Ag dissolution is comparatively reduced, possibly due to the formation of undesirable products such as sulfite (SO_3^{2-}) and dithionate ($\text{S}_2\text{O}_6^{2-}$) ions. This is supported by the Eh-pH diagram for the S- H_2O system, which indicates that these species are thermodynamically stable within the corresponding pH and redox potential (Figure 4b) regions [15].

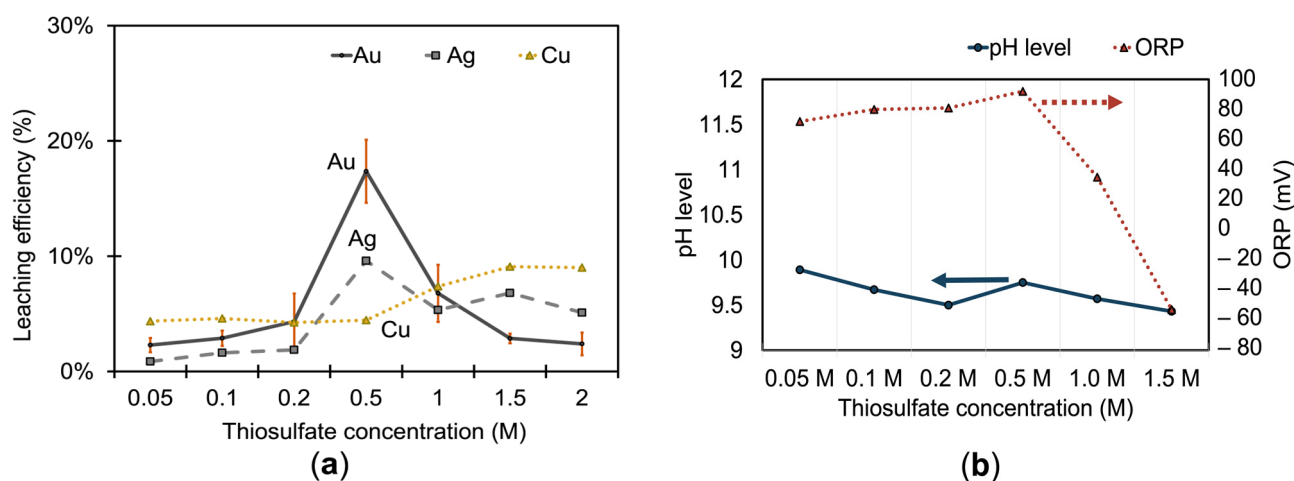


Figure 4. Effect of thiosulfate: (a) metal leaching efficiency and (b) pH level and ORP. Leaching conditions: 0.1 M Cu^{2+} , 0.05 M NH_3 , a stirring rate of 400 rpm, a pulp density of 20%, a leaching time of 1 h, a temperature of 25 °C, and a pH of 10.

Moreover, high concentrations of thiosulfate tend to stabilize copper, widen the stability region for $\text{Cu}(\text{S}_2\text{O}_3)_3^{3-}$ instead of $\text{Cu}(\text{NH}_3)_4^{2+}$, and even precipitate Cu^{2+} , thus hindering the role of copper as an oxidant and restraining gold dissolution [24,28]. High concentrations of $\text{S}_2\text{O}_3^{2-}$ could also destabilize $\text{Cu}(\text{NH}_3)_4^{2+}$, as explained in Equation (12), further limiting its oxidizing ability in the leaching system. The relatively higher concentration of thiosulfate within the shorter leaching time used in this study also aligns with trends observed in similar systems [24,29–31], in which the concentrate used in this study, 0.5 M thiosulfate, was ideal for gold dissolution under the conditions used.

3.1.2. Effect of Copper (II) Ions on Metal Extraction

Leaching experiments designed to determine the optimum copper ion concentration were conducted under the following conditions: 0.5 M $\text{S}_2\text{O}_3^{2-}$, 0.05 M NH_3 , a stirring rate of 400 rpm, a pulp density of 20%, a leaching time of 1 h, a temperature of 25 °C, and a pH of 10. Gold dissolution in thiosulfate solution in the presence of air is very slow, but copper (II) has been reported to be a better oxidant for dissolving gold at a faster rate, demonstrating a 10-fold rate increase [14]. However, not only gold but also silver and copper are affected by the presence of copper (II) ions. As shown in the results in Figure 5a, the leaching efficiency of gold increases with a concentration of $\text{Cu}(\text{II})$ of up to 0.1 M and

then slightly decreases, which is a trend similarly observed for silver and copper. The leaching efficiency for silver shows significant improvement at a Cu(II) concentration of 0.2 M, reaching a peak, but then slightly diminishes as the copper concentration continues to increase. Copper extraction is quite low at smaller concentrations of Cu(II) but exhibits a substantial increase at a concentration of 0.1 M, after which it again decreases, suggesting an optimal Cu(II) concentration for the leaching process of these metals.

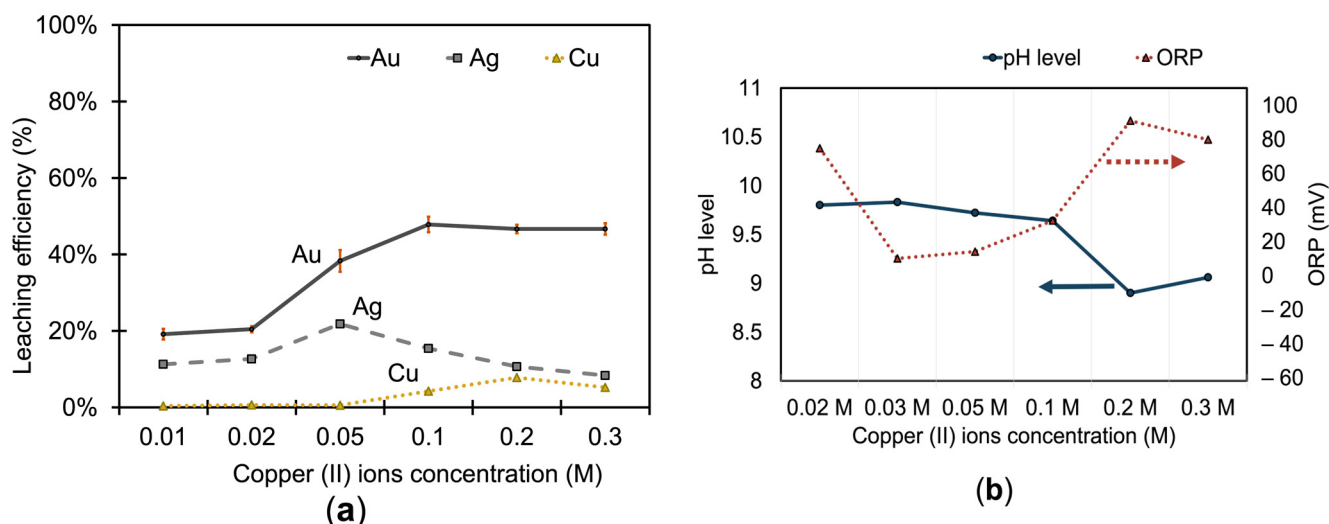
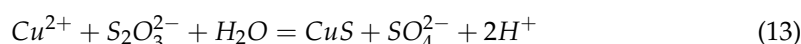
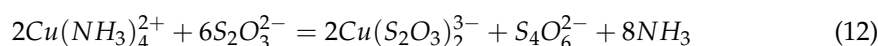
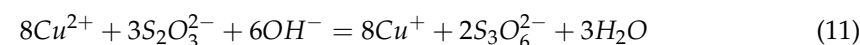
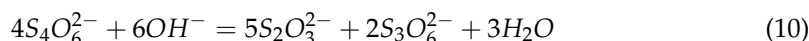
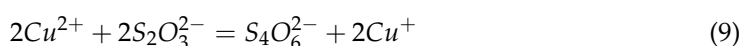


Figure 5. Effect of copper (II) ions: (a) metal leaching efficiency and (b) pH level and ORP. Leaching conditions: 0.5 M $S_2O_3^{2-}$, 0.05 M NH_3 , a stirring rate of 400 rpm, a pulp density of 20%, a leaching time of 1 h, a temperature of 25 °C, and a pH of 10.

This pattern for all three metals—gold, silver, and copper—is due to an increase in the copper concentration, which narrows the region of stability for $Cu(NH_3)_4^{2+}$ and $Cu(S_2O_3)_5^{5-}$ and expands the stability region for CuO , Cu_2O , and Cu_2S [15,29]. Additionally, as Cu (II) ions' oxidizing properties are high, higher concentrations can lead to degradation of $S_2O_3^{2-}$ into some by-products, such as tetrathionate ($S_4O_6^{2-}$), trithionate ($S_3O_6^{2-}$), sulfate (SO_4^{2-}), cyclo- S_8 , and copper sulfide, Cu_2S (Equations (9)–(13)).



High concentrations of copper (II) may therefore not only hinder the extraction of gold but also the leaching efficiency of silver and copper due to the formation of these precipitates [21,25,29,32].

3.1.3. Effect of Ammonia on Metal Extraction

The use of ammonia in the copper–thiosulfate leaching system serves several purposes: it minimizes the decomposition of thiosulfate into polythionates [33], stabilizes the copper (II) complexes [26], helps to maintain a stable pH, and improves the leaching kinetics [28]. The impact of ammonia on the dissolution of gold, silver, and copper was examined by varying the concentrations of ammonia from 0.1 M to 3 M while keeping other parameters constant: 0.5 M $S_2O_3^{2-}$, 0.1 M Cu^{2+} , a stirring rate of 400 rpm, a pulp

density of 20%, a leaching time of 1 h, a temperature of 25 °C, and a pH of 10. For gold, leaching efficiency improved progressively with a rising ammonia concentration up to 1.0 M, achieving its highest observed recovery, followed by a slight decline. This aligns with prior studies [13,31], in which moderate ammonia levels enhance gold dissolution by stabilizing the $\text{Au}(\text{S}_2\text{O}_3)_2^{3-}$ complex.

However, the extraction rates for all three metals—gold, silver, and copper—experienced a decline at higher ammonia concentrations (more than 1.0 M). The concentration of Cu (II) ions in the solution, which is representative of the oxidizing agent ($\text{Cu}(\text{NH}_3)_4^{2+}$) for gold, started to decrease from 1.68×10^{-5} M to 2.18×10^{-6} M with increasing ammonia concentrations (Figure 6c). This decline could be attributed to an increased pH level as well, which reduces the thermodynamic stability of $\text{Cu}(\text{NH}_3)_4^{2+}$ and $\text{Cu}(\text{S}_2\text{O}_3)_3^{3-}$ while expanding the stability regions of solid copper species such as Cu_2S , CuO , and Cu_2O [15,29]. Such precipitation would hinder the catalytic effect of copper on the leaching process for gold and also affect the leaching efficiencies of silver and copper. This indicates that there is an optimal ammonia concentration above which the benefits of stabilization give way to negative effects due to the over-stabilization and subsequent precipitation of copper.

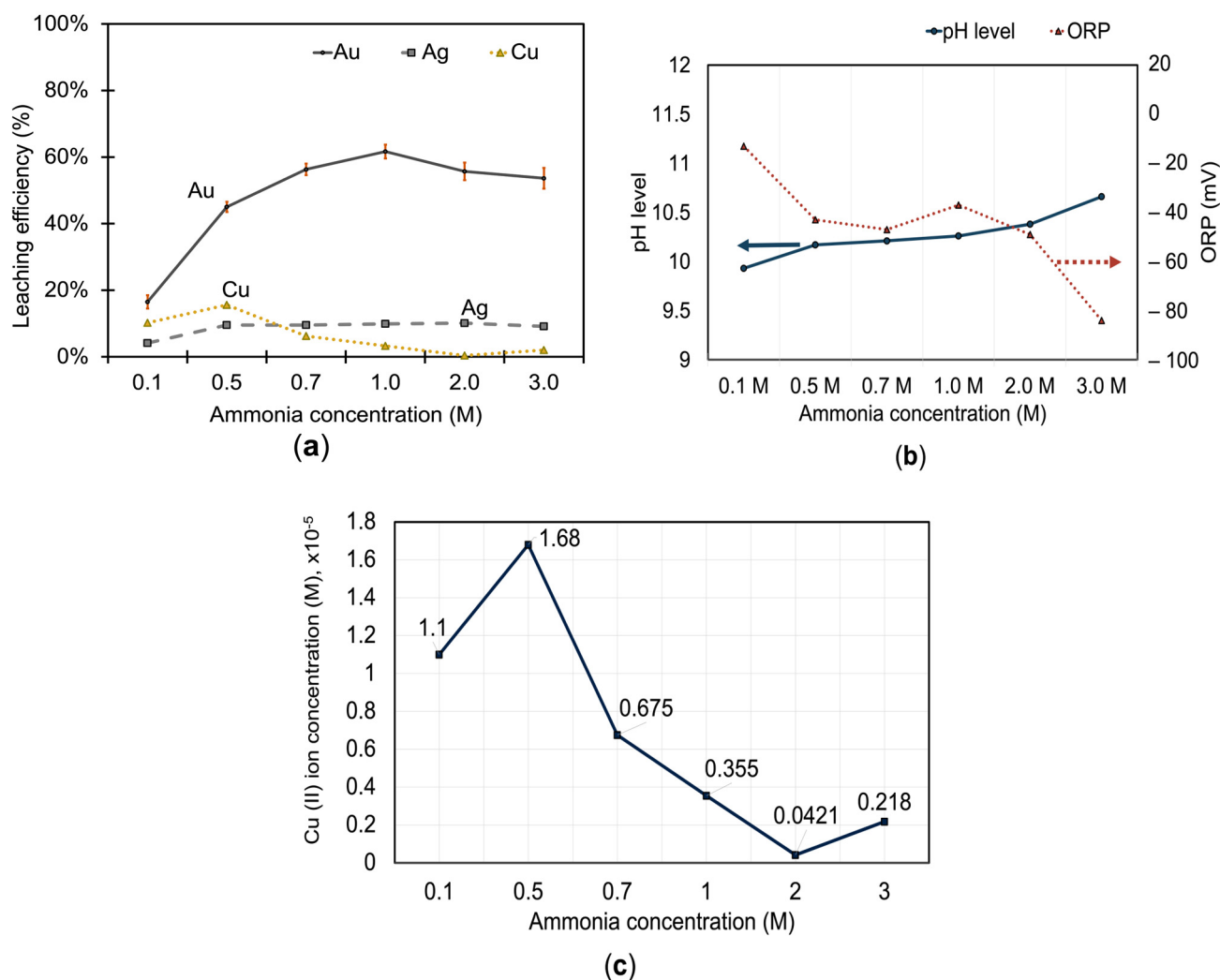


Figure 6. Effect of ammonia: (a) metal leaching efficiency; (b) pH level and ORP; and (c) quantitative variation of ammonia and copper (II) ions. Leaching conditions: 0.5 M $\text{S}_2\text{O}_3^{2-}$, 0.1 M Cu^{2+} , a stirring rate of 400 rpm, a pulp density of 20%, a leaching time of 1 h, a temperature of 25 °C, and a pH of 10.

3.1.4. Effect of the Solid-to-Liquid Ratio on Metal Extraction

A solid–liquid ratio (w/v) ranging from 10 to 50% was investigated. The experimental conditions used for each variable in Figure 7 are summarized in Table 2. The results in Figure 7a show higher extraction at a low pulp density due to the easy exposure of the solids to the leach solution. Gold dissolution in dense slurry suffers somewhat due to hindered contact between leach reagents and the gold surface because of particle mass transfer limitations. In addition, the concentrations of the reagents may have been insufficient for higher pulp densities [21]. Silver and copper also showed higher extraction rates at this low pulp density, measuring 36% and 25%, respectively. From an industrial perspective, lower pulp density may improve extraction but increases the cost of reagent consumption and reduces processing capacity. Thus, an economic balance between reagent use and extraction efficiency must be optimized for scalability.

3.1.5. Effect of the Stirring Rate on Metal Extraction

Stirring is essential for agitating and mixing solids with the leach solution, aerating the mixture, and intensifying the leaching reaction. Figure 7b presents the outcomes of metal extraction at various stirring speeds. In general, leaching efficiency decreased with higher stirring rates because excessive swirling of the slurry led to excessive oxygen dissolution in the solution. This behavior differs from cyanide leaching systems, which require air or oxygen. Furthermore, high stirring rates exacerbate undesirable side effects, such as the simultaneous decomposition of thiosulfate and the formation of Cu(I) ions [34]. These findings suggest that over-agitation may lower the process efficiency and reduce reagent stability, emphasizing the need to determine the optimal stirring rate to prevent unnecessary energy use and reagent waste. Based on Figure 7b, an optimal stirring rate of 350 rpm was determined.

3.1.6. Effect of the pH Level on Metal Extraction

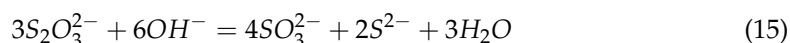
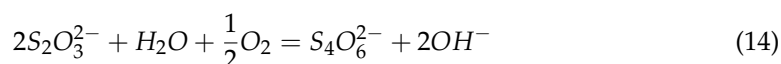
A pH above 9 is commonly maintained in this system because thiosulfate tends to decompose quickly at pH levels below 9. In this study, a range of pH levels between 9.5 and 12.0 were tested individually to determine the optimum conditions for leaching the concentrate. Contrary to previous reports suggesting that a stable pH of 10 is necessary [28], our current results indicate that a pH of 12 is more favorable, resulting in higher gold dissolution rates, as seen in Figure 7c.

This improved performance at a higher pH can be explained by the enhanced stability of thiosulfate and the increased formation of stable copper–amine–thiosulfate complexes, which are known to facilitate gold leaching more efficiently at elevated pH levels.

The favorable outcome at a pH of 12 can be attributed to the availability of a broader copper ammine complex region at high reagent concentrations, making this condition particularly advantageous for the process [15]. Silver and copper dissolve differently depending on the pH level. Silver recovery varies unpredictably, peaking at a pH of 9.5 but dropping at mid-range values. In contrast, copper dissolution steadily increases with the pH level, reaching its highest level at a pH of 12.0. This difference suggests that copper benefits from stable ammonia complexes at higher pH levels, while silver is affected by a sharp drop in redox potential (E_h) at pH levels of 11.0 or higher, reducing its ability to dissolve. From a practical view, maintaining a higher pH level may involve increased ammonia usage and control, but the improved gold recovery could outweigh the cost under optimized conditions. Therefore, a pH of 12 was identified as the optimal condition for this system due to its enhanced ability to form stable complexes with gold and copper, along with significantly reduced thiosulfate degradation. These findings highlight copper's resistance to alkaline conditions compared to silver's sensitivity to redox changes.

3.1.7. Effect of Temperature on Metal Extraction

In general, leaching efficiency increases with higher temperatures [30,35,36]. To verify whether this behavior holds in our system, the effects of temperature on thio-sulfate leaching were investigated. The results in Figure 7d show that [32] at high temperatures, gold dissolution declines rapidly because the solution becomes unstable due to the (a) loss of ammonia (i.e., evaporation) and (b) decomposition of thiosulfate (Equations (14) and (15)) [25,29,30,37], while the formation of cupric sulfide escalates (Equation (13)) [29]. Silver and copper follow a similar trend, with their highest dissolution rates at 25 °C (55.56% for silver and 25.04% for copper) and a noticeable decline as the temperature increases. Although Sitando et al. and Bae et al. have reported high gold dissolution at high temperatures (60 °C) [25,29,30], it can be surmised from Abbruzzese et al. that such a result is possible for a short time when high dosages of reagents are used [29]. Therefore, moderate temperatures, such as 25 °C, offer more stable and energy-efficient conditions for industrial applications, especially when aiming for low reagent decomposition and minimal ammonia loss.



3.1.8. Effect of Time on Metal Extraction

Figure 7e presents the results of leaching over 12 h. Rapid gold dissolution occurred in the first hour, wherein 80% of gold was extracted, then increased by 10% in the second hour and plateaued at 90%. Bas et al. reported a similar trend, but with a lower gold extraction of 70% [26]. The plateau observed after 2 h can be attributed to the depletion of readily leachable gold surfaces and the reduction in oxidant activity over time, particularly due to thiosulfate degradation and partial Cu precipitation. Extending the time to 12 h of leaching only increased both silver and copper extraction by 15%. However, longer leaching durations not only require additional operational time and energy but also lead to increased copper dissolution, which complicates downstream gold recovery processes. From a scalability perspective, a shorter leaching time (2 h) offers a practical and economical solution with high gold extraction and minimized reagent degradation, making the process more viable for industrial adoption. A leaching time of 2 h is considered ideal for the concentrate used in the present study.

The increase in gold leaching to over 80% was due to the synergistic effects of optimized reagent concentrations and controlled physicochemical parameters, which enhanced the stability and reactivity of the gold–thiosulfate complex, thereby improving the kinetics of the gold dissolution process. The optimized leaching conditions were as follows: 0.5 M $S_2O_3^{2-}$, 1.0 M NH_3 , 0.1M Cu^{2+} , a stirring rate of 350 rpm, a pH of 12, a pulp density of 10% solids, a temperature of 25 °C, and a leaching time of 2 h. Under the optimized conditions, the extraction rates for gold, silver, and copper were 87%, 43%, and 11%, respectively.

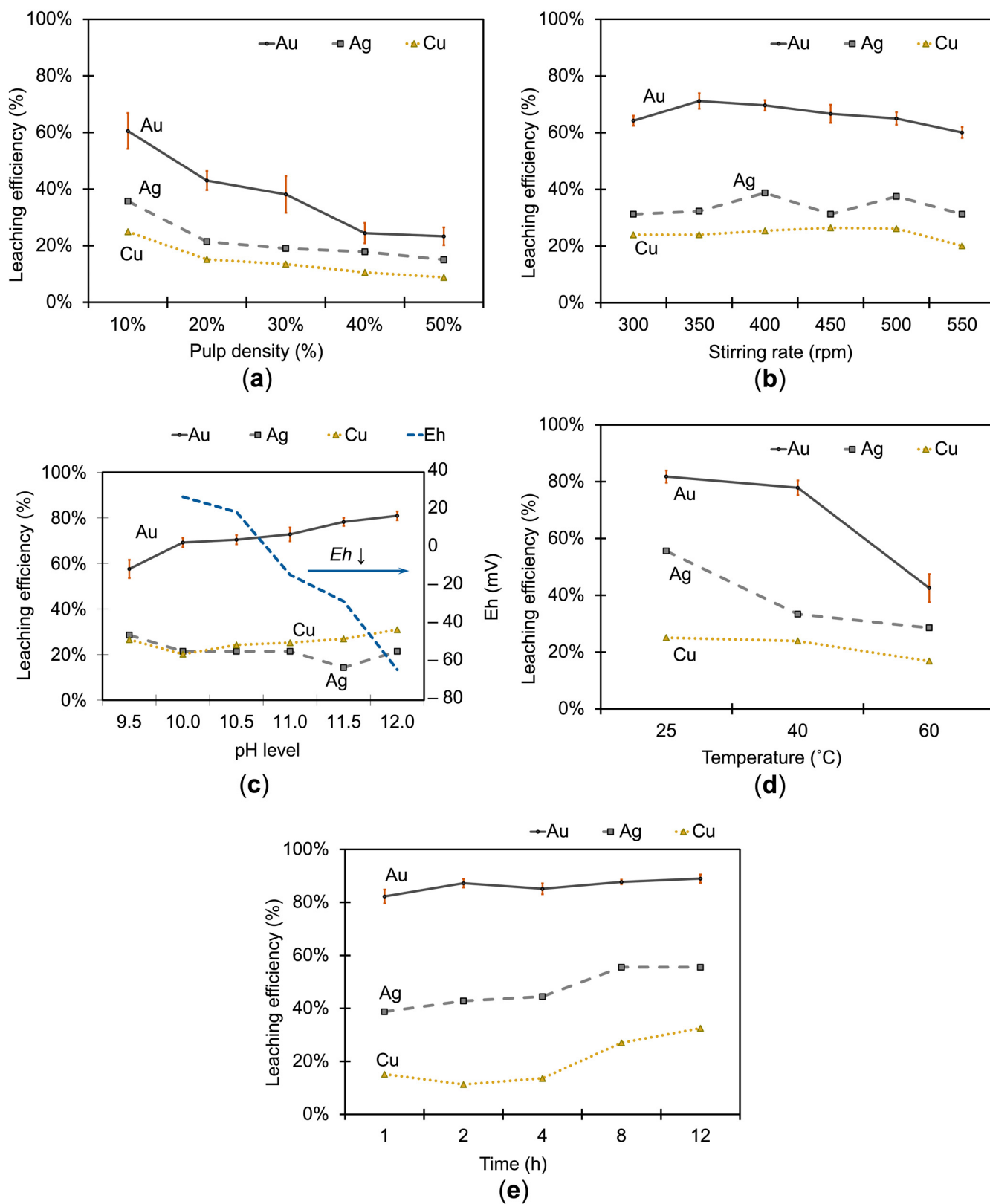


Figure 7. Effects of (a) pulp density, (b) stirring rate, (c) pH level, (d) temperature, and (e) time.

Table 2. Experimental conditions used for each variable in Figure 7.

Subfigure	Variable Studied	Values Tested	Constant Conditions
Figure 7a	Pulp density	10–50%	0.5 M $S_2O_3^{2-}$, 0.1 M Cu^{2+} , 1.0 M NH_3 , a stirring rate of 400 rpm, a leaching time of 1 h, a temperature of 25 °C, and a pH of 10
Figure 7b	Stirring rate	300–550 rpm	0.5 M $S_2O_3^{2-}$, 0.1 M Cu^{2+} , 1.0 M NH_3 , a pulp density of 10%, a leaching time of 1 h, a temperature of 25 °C, and a pH of 10
Figure 7c	pH level	9.5–12.0	0.5 M $S_2O_3^{2-}$, 0.1 M Cu^{2+} , 1.0 M NH_3 , a pulp density of 10%, a stirring rate of 350 rpm, a leaching time of 1 h, and a temperature of 25 °C
Figure 7d	Temperature	25–60 °C	0.5 M $S_2O_3^{2-}$, 0.1 M Cu^{2+} , 1.0 M NH_3 , a pulp density of 10%, a stirring rate of 350 rpm, a leaching time of 1 h, and a pH of 12
Figure 7e	Time	1–12 h	0.5 M $S_2O_3^{2-}$, 0.1 M Cu^{2+} , 1.0 M NH_3 , a pulp density of 10%, a stirring rate of 350 rpm, a temperature of 25 °C, and a pH of 12

3.2. Effects of Additives on Thiosulfate Decomposition

To improve and enhance the leaching process, additives were introduced in subsequent tests. The primary objectives of incorporating additives are (1) to reduce the decomposition of thiosulfate, thereby preserving its concentration and effectiveness throughout the leaching process, and (2) to increase the leaching efficiency, particularly for gold, but potentially also enhancing the extraction efficiency of silver and copper. The precise impact of the additives, whether in improving the overall extraction yields or in facilitating the more selective leaching of gold, is a focal point of the ensuing evaluations and analyses.

The chosen additive concentration of 0.1 M in this study was selected to be equal to the copper ion concentration (0.1 M Cu^{2+}) to maintain a balanced chemical environment and ensure effective interactions between copper and the stabilizing additives. This approach aimed to optimize gold dissolution while preventing excessive reagent consumption and maintaining solution stability.

DETA is known for its strong chelating properties, which can help in stabilizing copper ions in solution, thereby preventing unwanted side reactions that consume thiosulfate. Additionally, its ability to form stable complexes with transition metals enhances the overall selectivity of the leaching process, thereby reducing the consumption of thiosulfate and improving the efficiency of gold extraction.

Figure 8a shows the results for metal extraction and thiosulfate consumption as a function of time when DETA was added. Gold extraction initially increased, followed by a subsequent reduction. Silver and copper extraction gradually increased overall. Thiosulfate consumption increased initially and then decreased, which may reflect the changing stability of copper–ammonia complexes over time.

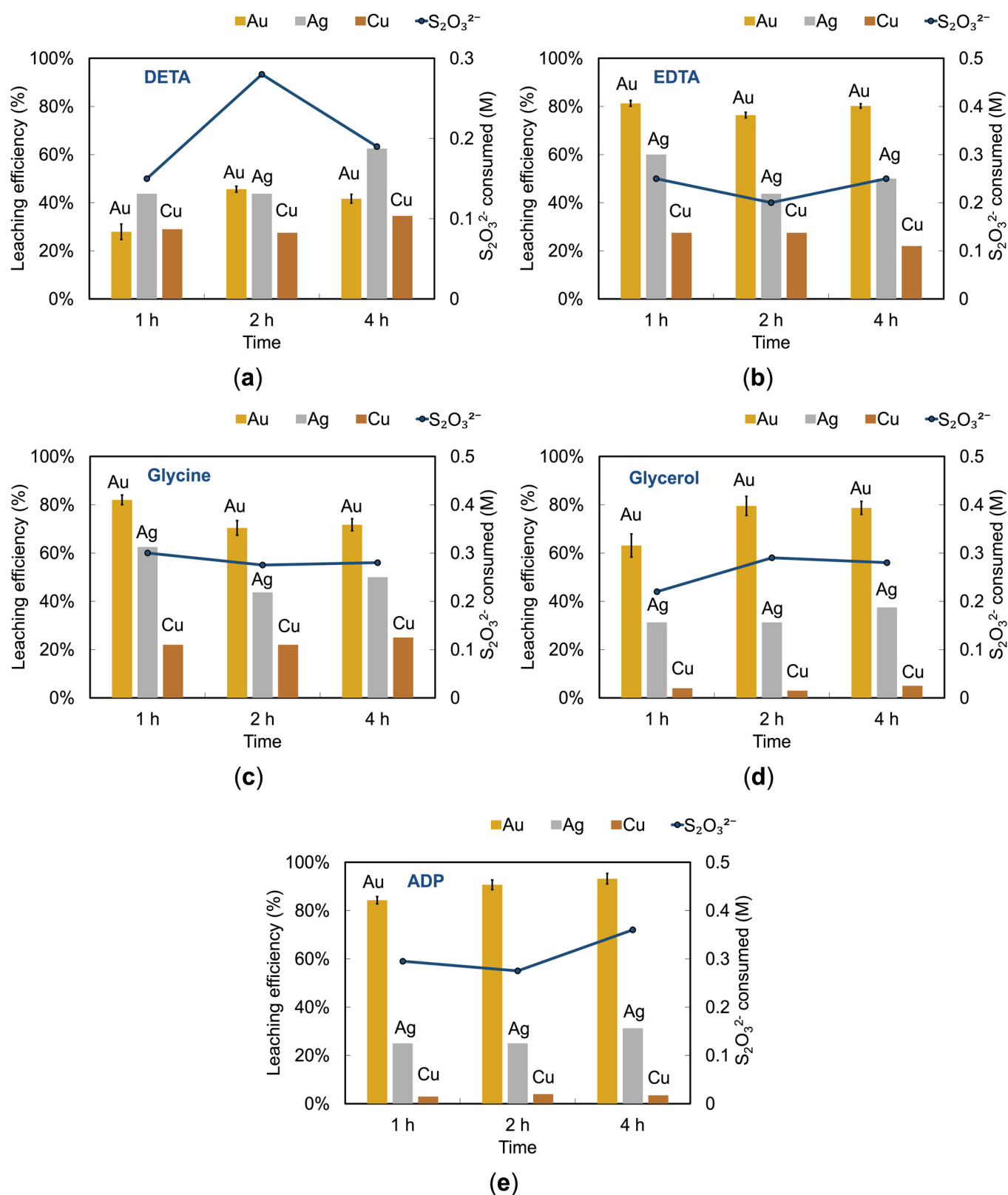


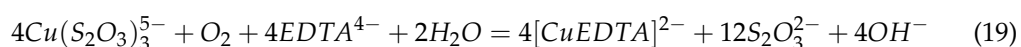
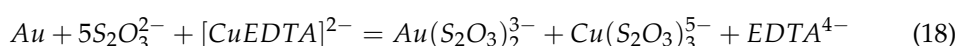
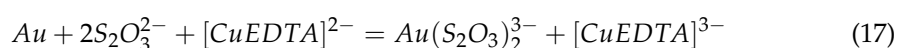
Figure 8. Ammonium-thiosulfate leaching of Au, Ag, and Cu with varying additives over time: (a) DETA, (b) EDTA, (c) glycine, (d) glycerol, and (e) ADP.

The observed fluctuations in gold extraction could be linked to the role of DETA in altering the surface chemistry of pyrite and other sulfide minerals [38]. Additionally, while DETA's ability to form stable complexes with copper ions improves the leaching process and initially increases gold extraction, it may also hinder gold leaching over time. This

gradual inhibition of catalytic oxidation is due to Cu(II), as some or all of the $\text{Cu}(\text{NH}_3)_4^{2+}$ complexes are converted into Cu(II)-DETA complexes. This explanation aligns with the initial increase and then a decline in gold extraction over time. Furthermore, DETA's impact on the leaching environment may extend to the stability of thiosulfate itself, which is crucial for gold dissolution.

EDTA is a powerful chelating agent that effectively binds to metal ions, thereby reducing their reactivity and preventing precipitation and unwanted side reactions. Its ability to stabilize Cu(II) ions is particularly advantageous in thiosulfate leaching systems, as it helps maintain the concentration of active thiosulfate species, thereby reducing the overall decomposition. Moreover, EDTA's formation of stable metal complexes can enhance the selectivity of the leaching process, particularly benefiting the extraction of precious metals like gold and silver.

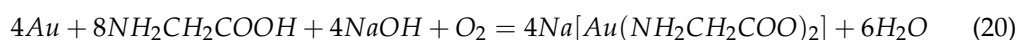
Figure 8b shows the effects of the EDTA additive on Au, Ag, and Cu extraction, along with its thiosulfate consumption. As shown in the figure, leaching efficiencies of approximately 80% for Au, 50–60% for Ag, and 20–30% for Cu were obtained with half of the thiosulfate (0.25 M) decomposition rate. In comparison to the DETA system, the results showed that higher extractions were obtained, which can be attributed to following reasons: EDTA can stabilize copper (II), which plays an important role in thiosulfate leaching system, prevent reactions with sulfide minerals [39], and favorably form complexes with metals including Cu and lead (Pb), thereby facilitating the high dissolution rates of precious metals [20,40]. The stability constants of $\text{Cu}(\text{NH}_3)_4^{2+}$ and Cu (II)-EDTA are 4.35 and 12.28, respectively, indicating that EDTA stabilizes the cupric ion significantly more than ammonia. This stronger stabilization by EDTA reduces the availability of free Cu (II) ions to form $\text{Cu}(\text{NH}_3)_4^{2+}$ complexes, thereby influencing the overall concentration of $\text{Cu}(\text{NH}_3)_4^{2+}$ in the system. The preference for Cu (II)-EDTA complex formation ensures that the Cu (II) species remain more stable and active within the leaching system, which enhances the efficiency of gold dissolution through the reactions described (Equations (16)–(19)). However, it is important to consider that the high dissolution of copper, facilitated by EDTA, may not always favor downstream gold recovery, as it could complicate the subsequent separation process.



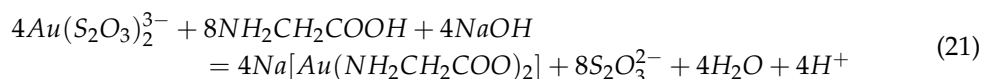
Glycine, an amino acid, serves as an effective complexing agent that stabilizes metal ions in solutions, thereby reducing the formation of unwanted precipitates. Its role in forming stable gold–glycine complexes ensures a higher initial rate of gold extraction. Furthermore, glycine helps to maintain the pH level and prevent the decomposition of thiosulfate by minimizing side reactions. This dual functionality not only enhances the gold leaching efficiency but also promotes the more sustainable use of thiosulfate.

Regarding the effect of glycine, Figure 8c reveals significant insights into the leaching behavior and thiosulfate consumption over time. In the initial hour, the gold dissolution reached approximately 80%, indicating a rapid leaching process. However, a notable decrease in gold leaching efficiency was observed over the subsequent hours. The initial gold dissolution rate can be attributed to the formation of a stable gold–thiosulfate complex, facilitated by the presence of glycine. Glycine acts as a stabilizing agent for the gold complex, forming a more stable gold–glycine complex, as indicated by the reaction mechanism

(Equations (20) and (21)) described in the study by Godigamuwa et al., 2023 [41] and expressed as follows:



In the glycine–thiosulfate system, the initial stage involves the rapid formation of the gold–thiosulfate complex, which is stabilized by glycine, converting it to a more stable gold–glycine complex, expressed as follows:



The decrease in gold leaching efficiency observed after the initial hour could be due to the partial decomposition or instability of the gold–glycine complex with prolonged exposure. This phenomenon aligns with the findings of Godigamuwa et al., 2023, where the stability of the leached gold was enhanced initially but showed fluctuations over time due to the dynamic nature of the complex formation and dissolution processes [41].

Glycine functions similarly to NH_3 by stabilizing Cu(II) and oxidizing gold [37,42]; hence, the gold extraction rate was also about 80% at 1 h of leaching time, together with Ag (63%) and Cu extractions (20%). Oraby and Eksteen reported on glycine as a lixiviant for gold [37]. Their work revealed that a higher concentration of glycine could enhance the gold dissolution, but the kinetics can be very slow. Above a pH of 12 and in the presence of glycine, copper forms passivating layers of tenorite (CuO) and cuprite (Cu_2O) [42], consequently hindering gold dissolution.

This study also noted a decrease in thiosulfate consumption from 0.3 M to 0.28 M over the same period. This reduction suggests that glycine not only aids in the stabilization of the gold complex but also improves the efficiency of thiosulfate usage. Glycine's presence likely reduces the formation of side reactions that consume thiosulfate, thereby optimizing the leaching process.

Glycerol, a trihydroxy alcohol, acts as an effective stabilizing agent in leaching systems due to its ability to form hydrogen bonds, which can help maintain the integrity of thiosulfate in solution. Its use in minimizing thiosulfate decomposition is critical, as it reduces the need for the replenishment of the leaching agent, thereby cutting operational costs. Moreover, glycerol's properties as an emulsifier and stabilizer can prevent the formation of precipitates, ensuring a more efficient leaching process.

Glycerol, sometimes known as glycerin/glycerine or 1,2,3-propanetriol, is an alcohol that has three hydroxyl (OH) groups. Glycerol remains stable, although it can be reacted as an alcohol via the three (3) hydroxyl groups in its structure. Among its many properties, glycerol is an emulsifier that has been used in many everyday products, such as food and ointments [43]. However, the use of glycerol in the processing of ores/concentrates is rare. The reagent was explored for its potential in the cyanide-based gold leaching process to enhance the extraction efficiency, stabilize the pH, and mitigate the environmental impact. Its application, however, has not been investigated in thiosulfate systems, making it a novel topic that is addressed here for the first time. In this present study, three (3) features have been discovered by using glycerol as an additive. As shown in Figure 8d, the presence of glycerol helps to minimize thiosulfate decomposition, hinders copper dissolution, and enhances Au and Ag dissolution. The results show that about 80% of Au, 31% of Ag, and less than 2% of Cu were extracted from the ores in 2 h.

The incorporation of ammonium dihydrogen phosphate (ADP) into the thiosulfate leaching system has demonstrated significant improvements in both leaching efficiency and chemical stability. ADP, known for its buffering capacity, plays a crucial role in maintaining

pH stability, which is essential for optimizing the thiosulfate-based gold extraction process. This stabilization effect is particularly important in preventing the rapid decomposition of thiosulfate, especially at lower pH levels, thereby reducing overall reagent consumption.

As illustrated in Figure 8e, gold leaching efficiency remains high over time, with 93% recovery after 4 h, accompanied by a 31% increase in silver dissolution and suppressing copper dissolution, while thiosulfate consumption stays relatively stable. This consistency underscores ADP's role in sustaining an optimal leaching environment, minimizing the need for frequent reagent replenishment. Subsequent analysis in Figure 9 shows that ADP increases gold (Au) leaching efficiency to approximately 91%, compared to 87% without additives, while also reducing thiosulfate consumption from 0.37 M to 0.28 M. These improvements highlight ADP's effectiveness in making the process both cost-effective and environmentally friendly.

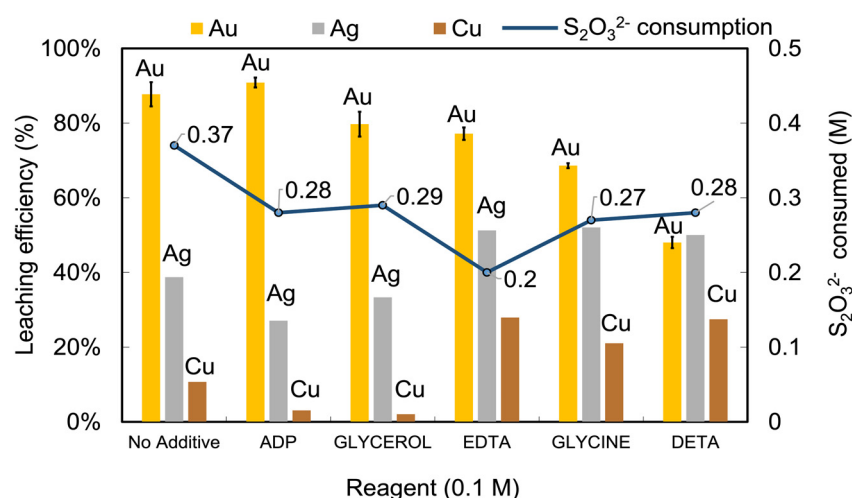


Figure 9. Effect of 0.1 M additives on metal extraction (0.5 M $S_2O_3^{2-}$, 0.1 M Cu^{2+} , 1.0 M NH_3 , a stirring rate of 350 rpm, a pulp density of 10% solids, a pH of 12, a leaching time of 2 h, and a temperature of 25 °C).

Chemically, ADP dissociates in water to release phosphate ions ($H_2PO_4^-$) and ammonia (NH_4^+). The phosphate ions interact with copper ions (Cu^{2+}), forming stable copper-phosphate complexes that inhibit excessive copper oxidation and precipitation. This complexation reduces the availability of free Cu^{2+} ions in the solution, effectively suppressing copper dissolution. Moreover, the formation of these copper-phosphate complexes can lead to the precipitation of colloidal copper (II) phosphate species on the mineral surface, which contributes to surface passivation by blocking reactive sites that would otherwise facilitate copper dissolution. This dual action of complex formation and surface passivation is crucial for maintaining copper in a stabilized form, thus preserving its catalytic role in the thiosulfate leaching of gold while minimizing copper loss. Furthermore, these phosphate ions help to de-passivate the gold surface, thereby inhibiting the formation of detrimental species, such as tetrathionates and polythionates, that could otherwise hinder the leaching process [18,20]. The ammonium ions further contribute to the stability of the leaching solution by forming stable ammonium-thiosulfate complexes, thereby reducing the rate of thiosulfate decomposition.

In conclusion, the addition of ADP creates a controlled and stable environment in the thiosulfate leaching system, enhancing gold extraction efficiency while significantly reducing thiosulfate consumption. These characteristics highlight ADP's potential as a key additive for promoting sustainable and economically viable gold extraction, with implications for broader applications in other hydrometallurgical processes.

The summarized results using various additives (i.e., diethylenetriamine (DETA), glycine, ethylenediaminetetraacetic acid (EDTA), glycerol, and ammonium dihydrogen phosphate (ADP)) are shown in Figure 9. The significant effect of the additives was the reduction in the amount of $\text{S}_2\text{O}_3^{2-}$ consumed. In the absence of the additives, the $\text{S}_2\text{O}_3^{2-}$ consumption was 0.37 M (74%), but in the presence of additives, the decomposition rate decreased to 0.2–0.3 M (40–50%).

DETA, glycine, and EDTA enhanced copper dissolution by stabilizing the cupric ion and reducing foreign ion interference but lowered gold dissolution at excessive dosages due to the formation of more stable complexes that hinder the leaching process. Under carefully controlled conditions, EDTA, glycine, and DETA have the potential to leach gold, silver, and copper. Moreover, the presence of EDTA can decrease the formation of the S layers generated from the thiosulfate decomposition [44]. The results showed that thiosulfate decomposition also decreased from about 0.4 M to 0.2 M. Some studies have shown the potential of glycine as a complexing agent (Equations (12) and (13)) [41,45].

Unfortunately, as a complexing agent in an alkaline environment, glycine enables the effective leaching of copper but yields a decreased leaching rate of gold under specific conditions, such as higher pH levels. However, the use of glycine has made it possible to adsorb gold and silver glycinate complexes onto activated carbon effectively, facilitating the recovery process of these metals [46,47].

The results of ADP addition were quite similar to those in the absence of the additive, but the thiosulfate decomposition rate was much lower [44], implying that glycerol is a potential reagent for applications in processes in which copper suppression is required.

The effects of various additives, such as diethylenetriamine (DETA), glycine, ethylenediaminetetraacetic acid (EDTA), glycerol, and ammonium dihydrogen phosphate (ADP), were examined. The additives were found to reduce the consumption of thiosulfate, resulting in increased gold leaching. However, DETA, glycine, and EDTA enhanced copper dissolution while lowering gold dissolution. Glycerol showed potential for copper suppression but caused a slight drop in gold extraction. EDTA was found to stabilize copper (II) and prevent its reaction with sulfide minerals. Glycerol was identified as a potential additive for ore processing, minimizing thiosulfate depletion, hindering copper dissolution, and promoting silver dissolution. ADP improved gold extraction and silver dissolution while suppressing copper extraction, highlighting its potential applicability in optimizing precious metal recovery processes.

3.3. Kinetic Analysis of Gold Leaching

The incorporation of ammonium dihydrogen phosphate (ADP) into the thiosulfate leaching system significantly influences both the leaching kinetics and the solution chemistry, thereby improving gold extraction while reducing reagent degradation. To better understand the leaching behavior, kinetic modeling was conducted using a pseudo-first-order kinetic approach, where $\ln(C_t)$ was plotted against time (t) to derive reaction rate constants (k) from the slope of the trendlines. The kinetic equations derived from experimental data (Figure 10) are as follows:

- Non-additive system: $y = 0.0881x + 4.7017$ ($R^2 = 0.9625$);
- Additive (ADP) system: $y = 0.0849x + 4.772$ ($R^2 = 0.948$).

Here, y represents $\ln(C_t)$, x is the time in hours, and the slope corresponds to the rate constant k . These results confirm a significantly enhanced reaction rate in the presence of ADP ($k = 0.0455 \text{ h}^{-1}$) compared to the non-additive system ($k = 0.047 \text{ h}^{-1}$), indicating improved gold dissolution efficiency due to thiosulfate stabilization.

This model supports the trend observed in the original kinetic data (Figure 10), where a separate analysis showed that the linear regression of the additive system ($R^2 = 0.9478$)

exhibited a steeper slope (0.0455) than that of the non-additive system (0.047, $R^2 = 0.9534$), both of which were evaluated as $\ln(k)$ versus time. Both modeling approaches consistently demonstrate that the presence of ADP accelerates gold leaching kinetics. This improvement aligns with previous findings demonstrating that orthophosphate compounds promote gold dissolution by stabilizing thiosulfate against oxidative degradation through copper(II) complexation [20].

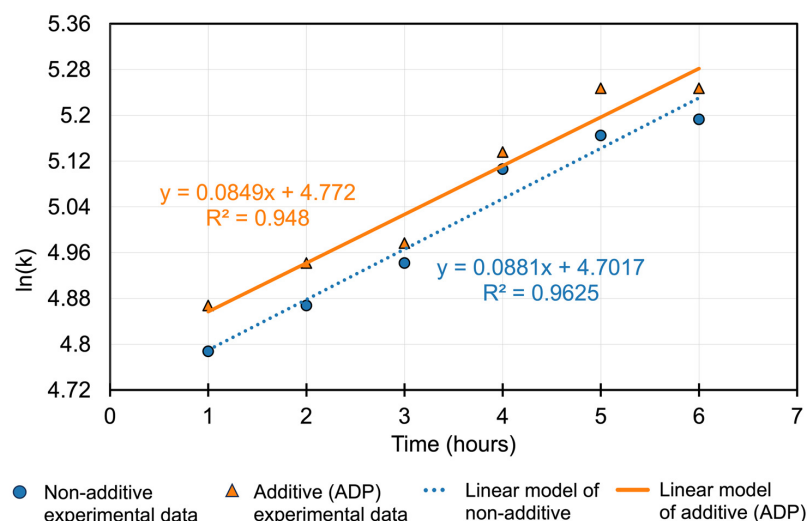


Figure 10. Kinetic plot ($\ln(k)$ vs. time) for additive (ADP) and non-additive leaching systems. Lines represent linear regression fits with corresponding R^2 values.

Figure 11a,b additionally highlight the buffering role of ADP in maintaining more stable pH and redox (Eh) conditions during the leaching process. In the non-additive system (Figure 11a), the pH declines rapidly within the first 4 h, accompanied by a sharp drop in Eh, suggesting increased thiosulfate decomposition due to acidification. In contrast, the ADP-stabilized system (Figure 11b) maintains a more gradual and stable pH decline with a correspondingly less consistent Eh behavior. This buffering effect minimizes conditions that are favorable for thiosulfate degradation and the formation of detrimental species, such as tetrathionates and polythionates, which can passivate the gold surface and hinder leaching [18].

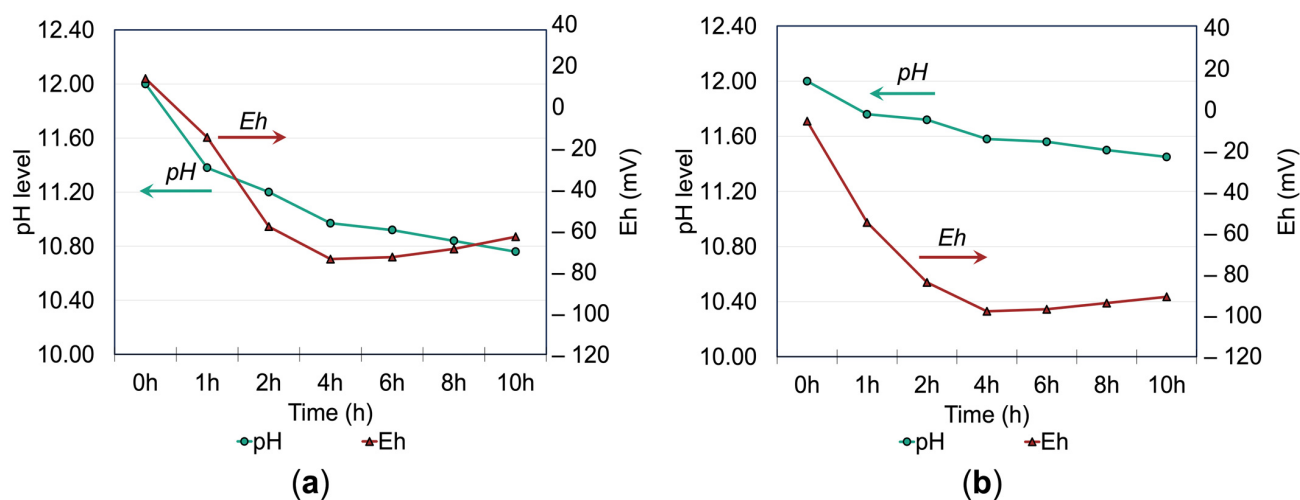


Figure 11. Effect of ADP on pH and redox potential (Eh) evolution during thiosulfate leaching: (a) trends of pH and Eh over time in the absence of ADP; (b) trends of pH and Eh over time with ADP.

The dissociation of ADP releases phosphate ions (H_2PO_4^-) and ammonium (NH_4^+), both of which contribute to solution stability. Phosphate ions form complexes with Cu^{2+} ions, stabilizing them in solution and preventing their precipitation as copper hydroxides or phosphates. This stabilization ensures the continued catalytic role of copper without excessive consumption, a behavior similarly observed with orthophosphate and hexametaphosphate additives [20]. Moreover, these phosphate species reduce the interaction between thiosulfate and sulfide minerals, as seen in sulfide ore systems in which orthophosphate enhances leaching kinetics and suppresses side reactions [20].

The low copper leaching efficiency in the ADP-enhanced thiosulfate system is primarily due to the formation of stable copper–phosphate complexes, which reduce free Cu^{2+} availability and limit its dissolution. At higher ADP concentrations, phosphate ions precipitate copper as colloidal copper (II) phosphate species [18], removing it from the solution and decreasing its overall mobility. This behavior, which is consistent with the effects observed for orthophosphate and hexametaphosphate, diminishes copper’s catalytic role in thiosulfate oxidation and contributes to reduced copper leaching while stabilizing thiosulfate and enhancing precious metal selectivity.

4. Conclusions

The present study focused on the extraction of gold, silver, and copper from a high-sulfide-containing flotation concentrate using ammonia–copper–thiosulfate leaching. Various parameters were altered to optimize the leaching condition, and the impact of various additives on metal extractions and thiosulfate consumption was investigated.

During the optimization of leaching control parameters, the investigation identified the optimum conditions for maximizing gold extraction, including concentrations of 0.5 M of thiosulfate ($\text{S}_2\text{O}_3^{2-}$), 1.0 M of ammonia (NH_3), and 0.1 M of copper (Cu^{2+}), a pH level of 12, a stirring rate of 350 rpm, a solid density of 10%, a temperature of 25 °C, and a leaching duration of 2 h. These conditions showed extraction rates of 87% for Au, 43% for Ag, and 11% for Cu, with 74% of thiosulfate consumption.

Additionally, research employing various additives was conducted, focusing specifically on those that have been applied in other systems but are being explored for the first time within the thiosulfate system. This study is the first to systematically investigate the roles of glycerol and ADP as additives in the thiosulfate leaching system, demonstrating their potential to significantly reduce thiosulfate consumption and enhance metal extraction efficiency. Diethylenetriamine (DETA), glycine, and ethylenediaminetetraacetic acid (EDTA) showed potential for metal extraction, but with contrasting effects on gold and copper dissolution. Glycerol and ADP emerged as notable additives, minimizing thiosulfate consumption to concentrations of 0.28–0.29 M, inhibiting copper dissolution at around 4%, and promoting silver dissolution at 31%, with over 80% Au extraction.

This study demonstrates that non-cyanide gold extraction methods, specifically ammonia–copper–thiosulfate leaching, can be optimized to achieve high gold recovery rates while reducing environmental impacts. By reducing reliance on toxic cyanide, this research contributes to the advancement of more sustainable and environmentally friendly mining practices. The integration of additives not only enhances gold extraction efficiency but also significantly decreases thiosulfate consumption, making the process more cost-effective and sustainable. Furthermore, the findings from this research offer valuable insights into the application of such methods, specifically for high-sulfide-containing flotation concentrates. This addresses the critical concerns surrounding traditional techniques that rely on toxic cyanide and underscores the potential for these optimized methods to revolutionize gold extraction processes. By exploring alternative extraction methods with additive variations,

we establish a foundation for more sustainable and eco-friendly processing strategies that are adapted to the specific challenges associated with high-sulfide ores.

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